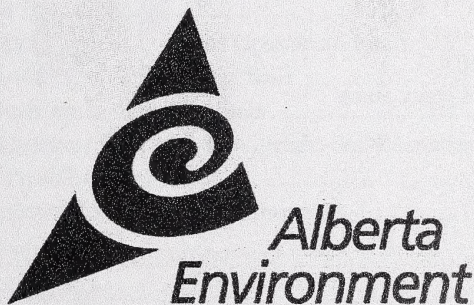


ALBERTA SOIL AND WATER QUALITY
GUIDELINES FOR HYDROCARBONS
AT UPSTREAM OIL AND GAS FACILITIES

VOLUME 1: PROTOCOL

September 2001

DRAFT



Pub. No: T/620

ISBN: 0-7785-1895-7 Printed Edition

ISBN: 0-7785-1898-1 On-line Edition

Web Site: <http://www.gov.ab.ca/env/>

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1. INTRODUCTION

The operation of upstream oil and gas facilities can result in the release of hydrocarbon compounds to the environment. This can be a concern either during the operation of the facility, or after decommissioning when land is returned to its former or a new use. Site closure is a term often used to describe regulatory acceptance that decommissioning is complete, and the land is ready to revert to its former or a new use. The *Alberta Soil and Water Quality Guidelines for Upstream Oil and Gas Sites* were developed to assist in environmental management and site closure of upstream oil and gas facilities in Alberta.

The upstream sector of the oil and gas industry includes activities associated with the extraction of oil and gas from the subsurface up to the point it reaches the refinery. Examples of upstream oil and gas facilities include well sites and gas plants. Refineries and facilities for the distribution and sale of refined products are not part of the upstream sector. The *Alberta Soil and Water Quality Guidelines for Hydrocarbons at Upstream Oil and Gas Facilities* specifically addresses releases of hydrocarbon mixtures from the upstream sector.

1.1 Approach

The approach taken in the development of these Guidelines follows the most recent regulatory guidance on management of upstream oil and gas sites (AENV 2000a), and on risk management at contaminated sites in Alberta (AENV, 2000b). Technically, the Protocol uses the Canada-Wide Standard for Petroleum Hydrocarbons in Soil (CCME, 2000) as a starting point with adaptations to Alberta conditions where appropriate. The approach in CCME (2000) was itself based on, and developed from, previous methodology developed by the CCME (1996).

1.2 Guideline Overview and Document Layout

The *Alberta Soil and Water Quality Guidelines for Upstream Oil and Gas Sites* are presented in three volumes:

Volume 1	Protocol
Volume 2	Guideline Development
Volume 3	Guideline Summary and User Guidance

Volume 1 (this volume) includes an overview of the project, provides background and rationale for the approach used, and develops the technical protocol used for guideline development. Volume 2 provides details of the guideline development process, including all chemical-specific information. Volume 3 summarizes guideline values, and provides user guidance. Volume 3 provides all the

information required by users of generic guidelines. Users wishing to develop modified generic guidelines or site-specific remediation objectives will find useful information in all 3 volumes.

The remainder of the current document (Volume 1) is organized as follows: Section 2 provides the technical framework for the guidelines, and describes in detail *which* guidelines were developed. Sections 3 and 4 describe *how* the soil guidelines were developed for human health and ecological pathways, respectively, including formulae and non chemical-specific parameters. Section 5 includes information on how the guidelines developed in Sections 3 and 4 were adapted to apply to different soil textures and to subsoil. Section 6 addresses guidelines for groundwater quality.

Volume 3 is the critical document for the application of these guidelines. Certain procedures and conditions described below have limited application as described in Volume 3.

2. TECHNICAL FRAMEWORK

The technical framework describes the format for the *Alberta Soil and Water Quality Guidelines for Upstream Oil and Gas Sites* and their application. The Guidelines:

1. provide a sound scientific basis for the management of petroleum hydrocarbon contamination at upstream oil and gas sites;
2. are consistent with Alberta Environment policy for managing such sites; and,
3. draw on and develop the work done for the Canada-Wide Standard for Petroleum Hydrocarbons (CCME, 2000) in so far as it is applicable to upstream oil and gas sites in Alberta.

Key concepts are discussed below.

2.1 Types of Site Closure

In the document "*A Proposed Management Framework and Associated Remediation Objectives for Upstream Oil and Gas Sites in Alberta*", AENV (2000a) defines three potential closure conditions for Upstream Oil and Gas Sites in Alberta:

- Unconditional Closure;
- Conditional Closure; and,
- Deferred Closure.

Two of these - Unconditional Closure and Conditional Closure – are key concepts in the scope of this document and are described below.

Unconditional Closure implies that all normal activities that could occur under the land use designation are protected, (*i.e.*, land use is not restricted). Sites may be eligible for Unconditional Closure either i) by being “screened out” from further consideration after a rigorous Phase 1 assessment, ii) after analytical testing that shows compliance with the Unconditional Closure guidelines for soil and groundwater, or iii) after remediation and confirmatory analyses that show compliance with the Unconditional Closure guidelines for soil and groundwater (AENV, 2000a). This document provides the Protocol for developing guidelines for Unconditional Closure.

Conditional Closure is an option that may be available when technical or economic considerations make Unconditional Closure impractical. Conditional Closure is intended to be used at sites where certain restrictions on the land use are required to ensure that human and ecological health are protected. Conditional closure will normally involve institutional or engineered controls (*e.g.*, a restriction on groundwater usage) to manage risks until Unconditional Closure guidelines are met. Landowner participation will be a crucial element of any risk management plan involving Conditional Closure. In addition, certain technical and policy conditions (*e.g.*, removal of free phase hydrocarbons, characterization of the extent and stability of the groundwater plume, salinity of the groundwater) must be met for Conditional Closure to be an acceptable option. These issues are discussed more fully in the user guidance in Volume 3.

2.2 Levels of Site-Specific Information

The technical framework allows for three Tiers, corresponding to three levels of site-specific information:

- Tier 1 or generic guidelines;
- Tier 2 or modified generic, guidelines; and,
- Tier 3 or site-specific remediation objectives developed through a risk assessment.

The level of protection on which all three Tiers are based is identical.

2.2.1 Tier 1 - Generic Guidelines

This document provides the Protocol for generating generic guidelines. These guidelines are based on a set of parameters which allow reasonably conservative predictions of risk at most upstream oil and gas sites throughout Alberta. Tier 1 guidelines will be applicable to the majority of upstream hydrocarbon sites in Alberta. A few sites will have conditions that result in higher contaminant exposures than was assumed for the generic scenarios (*e.g.*, sites underlain by very coarse materials such as gravels). In such cases, Tier 1 guidelines will not apply, and a Tier 2 or Tier 3 approach will be required.

2.2.2 Tier 2 - Modified Generic Guidelines

There may be circumstances where, based on the conditions at a particular site, the generic guidelines are unnecessarily conservative. Or, as outlined above for certain sites, assumptions used for guideline development may be too liberal; triggering a Tier 2 or 3 approach. Accordingly, guidance is provided in Volume 3 on ways in which the generic guidelines can be modified for use at a particular site, including a discussion of parameters for which generic values could be replaced by site-specific values. Guidance is also provided on the information that would be required to demonstrate that such site-specific values were applicable at a given site.

2.2.3 Tier 3 - Site-Specific Risk Assessment

Large or complex sites may require a site-specific risk assessment and/or toxicity testing to develop appropriate remediation objectives. There is much regulatory guidance available to assist with this process, but such work is outside the scope of the present document.

2.3 Soil Type

Generic guidelines were derived for two soil types, Coarse Soil and Fine Soil. These soils are defined as having a median grain size greater or less than 75 microns, respectively. This definition is consistent both with previous work conducted in Alberta (e.g., AEP, 1994b) and the Canada-Wide Standard. Assumed properties for these two standard soils are taken from CCME (2000) and are summarized in Table 2.1.

2.4 Depth to Contamination

Separate guidelines were developed for surface soils and sub-soils. The rationale for this was that: i) some of the direct contact pathways apply to surface soils only, and ii) for some pathways (e.g., ecological soil contact, indoor vapour inhalation) a different guideline may be appropriate in subsoil to achieve the same level of protection as that achieved in surface soil. For consistency with CCME (2000), the split between surface soils and sub-soils was at 1.5 m depth. A discussion of how surface soil guidelines are adapted to be applicable to subsoils is included in Section 5.3.

2.5 Land Use

Previous work developing soil quality guidelines in Canada (e.g., CCME, 1996, 1997, and 2000) has focussed on four main land use types: agricultural, residential/parkland, commercial, and industrial. This document provides a Protocol for developing guidelines for these four land uses, and also a fifth land use. The “natural area” land use was defined as an area where permanent human occupation is not anticipated, and only occasional human presence is likely. Typically, natural area land use will be

applied to the forested parts of Alberta away from human habitation, and will correspond approximately to the “Green Area” of the Province. The other four land uses are as defined in CCME (2000).

2.6 Chemicals of Concern

The scope of work defined the chemicals of concern to include petroleum hydrocarbons. This project takes the work done by CCME (2000) in which guidelines were generated for four PHC fractions (F1, F2, F3 and F4), and expands the scope to include BTEX components as individual chemicals, and carcinogenic PAHs quantified as equivalent benzo(a)pyrene (BaP). Note that at many sites, significant concentrations of carcinogenic PAHs will not be expected based on the composition of the original petroleum hydrocarbon release. In such cases, analysis for carcinogenic PAH compounds will not be required. Volume 3 includes guidance on when PAH analysis is required, and how the concentrations of carcinogenic PAHs should be calculated as equivalent concentrations of benzo[a]pyrene (B(a)P). The four PHC fractions are defined by CCME (2000) in terms of an equivalent carbon number range, with BTEX and carcinogens specifically excluded and removed from the appropriate fraction under consideration. The chemicals of concern, including the equivalent carbon number ranges of the four fractions are summarized in Table 2.2.

The chemicals of concern in this project therefore include all petroleum hydrocarbons except for polar compounds. Polar compounds are hydrocarbons that include oxygen, nitrogen, and/or sulphur atoms, and are excluded from the scope of this project.

2.7 Pathways

There are a wide range of pathways by which chemicals of concern may reach human and ecological receptors. The pathways considered by this project are adapted from CCME (2000). Table 2.3 summarizes which pathways are considered for each land use. The rationale for including or excluding each pathway in the present document is discussed below.

2.7.1 Human Health – Pathways Included

The following four pathways are the same four human health pathways considered by CCME (2000). All four human health pathways are calculated for all land uses except that only the protection of potable groundwater is considered in natural areas.

- **Soil Ingestion** was included to account for small amounts of soil inadvertently consumed by humans. Applies to all land uses except natural areas (human exposure in natural areas is expected to be low).

- **Soil Dermal Contact** was included to account for absorption of chemicals of concern from soil adhering to exposed skin. Applies to all land uses except natural areas (human exposure in natural areas is expected to be low).
- **Indoor Vapour Infiltration** was included to account for exposure to volatile chemicals of concern being drawn into residences or workplaces from contaminated soil and groundwater. This pathway was calculated for agricultural, residential, commercial, and industrial land uses, but not for natural areas (buildings generally not present).
- **Protection of Potable Groundwater** was included to account for exposure to chemicals of concern in drinking water sourced from water wells, and applies to all land uses.

2.7.2 Human Health – Pathways Excluded

Certain pathways were considered in CCME (1996), but were not included in CCME (2000) and are not included in the present work. Brief reasons why each pathway was excluded from the guideline derivation process are provided below.

- **Ingestion/Dermal Contact With Surface Water** (*i.e.*, drinking or swimming in surface water fed by either contaminated groundwater or contaminated runoff). This pathway was not considered because it was expected to be a less sensitive pathway than ingestion of groundwater (from water wells) due to the dilution that will normally occur when contaminated groundwater discharges to a surface water body, and a generally low frequency of exposure.
- **Dust Inhalation.** Experience from conducting risk assessments in various areas of Alberta suggests that, for hydrocarbons, this pathway is usually insignificant compared to other pathways such as soil ingestion, ingestion of potable groundwater, and inhalation of indoor air.
- **Inhalation of Outdoor Air.** This pathway is not expected to be significant when compared to the inhalation of outdoor air, based on the large amount of dilution that occurs when a flux of contaminated vapour from an underground source mixes with outdoor air.
- **Ingestion of Milk, Meat/Game, Produce, and Fish.** Any of these pathways may be significant for compounds that tend to bioconcentrate into animal or plant matter. However, petroleum hydrocarbons do not tend to biomagnify through food webs (Suter, 1997), and so it is not anticipated that these pathways will be significant.

2.7.3 Ecological – Pathways Included

The following pathways for protection of ecological health are included. These are the same as the pathways considered by CCME (2000) with two exceptions: i) nutrient cycling was excluded for the

reasons provided in the following section, and ii) only soil ingestion, rather than soil and food ingestion, was considered for livestock and wildlife, as discussed below.

- ***Plant/Invertebrate Soil Contact.*** Plants form the base of the food web and invertebrates are essential to soil structure and function. Healthy plant and invertebrate life are central to soil quality. This pathway was calculated for all land uses.
- ***Soil Ingestion by Livestock/Wildlife.*** CCME (2000) includes a soil and food ingestion pathway for livestock. However, sufficient information on bioconcentration of hydrocarbons into food is not currently available, and this pathway was not calculated for any of the hydrocarbon fractions in CCME (2000). Hydrocarbons do not tend to bioconcentrate into plants (Suter, 1997). Therefore, for both scientific and pragmatic reasons, in the current work, exposure to contaminants in ingested soil, but not ingested food, was considered. This pathway was calculated for agricultural and natural areas land use only.
- ***Protection of Groundwater for Aquatic Life.*** Dissolved phase contaminants may be transported in groundwater to surface water bodies (e.g., creeks, wetlands, lakes, etc.) where adverse effects on freshwater aquatic life are possible. This pathway need only be considered when there is a surface water body within 300m downgradient of the source of contamination. Downgradient is considered to be any direction within 45 degrees either side of the calculated mean direction of groundwater flow. The distance of 300 m was selected as being greater than the length of the vast majority of groundwater plumes of dissolved hydrocarbon. This value is based on preliminary results from studies of hydrocarbon plumes in the upstream oil and gas industry in Western Canada currently being undertaken by the CORONA group (Consortium of Research on Natural Attenuation). The value of 300 m is also consistent with a compilation of 647 petroleum hydrocarbon plumes presented in Wiedemeier *et al.* (1999), in which it was determined that 98.1% of the plumes were less than 900 feet (274 m) long. This pathway was calculated for all land uses.
- ***Protection of Groundwater for Livestock and Wildlife Watering.*** Dissolved phase contaminants may be transported in groundwater to man-made or natural surface water bodies (dugouts, creeks, wetlands, lakes, etc.) where livestock or wildlife may drink from them and be exposed to contaminants. This pathway was calculated for natural areas and agricultural land use only.

2.7.4 Ecological – Pathways Excluded

The following pathways were included (but not calculated) in CCME (2000). They are excluded from the current work for the reasons given below.

- ***Ingestion of Plant Material by Livestock or Wildlife.*** As noted in the preceding section, this pathway was not included because petroleum hydrocarbons do not tend to bioconcentrate into plants (Suter, 1997).
- ***Nutrient Cycling*** by soil microbes is one of the vital processes in any healthy soil. Accordingly, the effect of contaminated soil on microbe nutrient cycling needs to be considered. Available data for this pathway are summarized in Volume 2. In all cases, the data are insufficient (by CCME, 1996 protocols) to calculate this guideline.

2.8 Receptors

2.8.1 Human

Humans are present in four out of the five land use scenarios – humans are not included in the natural area scenario due to an anticipated low exposure frequency. Note, however, that humans *are* considered in the protection of potable groundwater pathway for natural areas, based on the AENV (2001) definition of a domestic use aquifer. Human receptor parameters are summarized in Table 2.4.

Different approaches were taken towards selecting receptors for carcinogenic and non-carcinogenic chemicals of concern. For non-carcinogens, the most sensitive human life-stage for each land use was selected as being the critical receptor. The critical receptor for agricultural, residential, and commercial land use is a toddler (CCME, 2000). For industrial land use it is assumed that children do not have regular access, and the critical receptor is assumed to be an adult worker (CCME, 2000).

Potential adverse effects from carcinogens are cumulative over a lifetime, and so exposure duration is a major factor in determining the most sensitive receptor. Following guidance from CCME (1996), exposures to carcinogens were assessed by considering an adult exposed for a full lifetime. Guidelines were calculated at an incremental cancer risk of 10^{-5} .

2.8.2 Ecological

For the ecological soil contact and aquatic life pathways, the approach taken was to protect a generic ecological receptor. For the soil ingestion pathway and for the protection of groundwater for livestock and wildlife watering pathways, a specific receptor was selected to represent each land use. A dairy cow was used for agricultural land use and a mule deer for natural areas. Ecological receptor parameters are summarized in Table 2.5.

3. HUMAN HEALTH SOIL GUIDELINES

This section describes the general approach taken to derive human toxicological exposure limits, and then considers each of the human health pathways identified in Section 2.7.1. For each of these pathways, the equations used to calculate the guideline are those used in CCME (2000). Detailed explanations of the equations and parameters used are available in that document and are not reproduced here. Rather, the equations and parameters to be used are summarized, and places where the methodology or parameters used in this document differ from those used in CCME (2000) are emphasized.

Where appropriate, a brief description is provided of the transport processes that underlie the calculation of each guideline. This is followed by the equation that is used to calculate the guideline. Beneath each equation, the parameters are described, and the units specified. For non chemical-specific parameters, either a value is provided, or reference made to one of the Tables in this report. Values for chemical-specific parameters are provided in the guideline development work (Volume 2).

Note that the equations in this document follow standard mathematical convention in that multiplication is indicated by two parameters being adjacent with no operator symbol between them. Where this convention might be ambiguous, the multiplication operator (\times) is used explicitly.

3.1 Human Exposure Limits

Each of the human health based guidelines calculated in the following sections is based on a human exposure limit, which reflects the concentration or dose of a chemical of concern that is considered unlikely to cause adverse health effects in sensitive humans. These exposure limits are chemical-specific values, and as such are included in the guideline development work (Volume 2). However, the general approach is to use regulatory-approved limits where available, in the following order of preference:

- Health Canada;
- exposure limits used in the PHC Canada-Wide Standard (CCME, 2000); and,
- United States Environmental Protection Agency IRIS database (US EPA, 2001).

Exposure limits for carcinogens are expressed at an incremental cancer risk of 10^{-5} .

3.2 Soil Ingestion

The soil quality guideline for soil ingestion (SQG_{SI}) was calculated in the same way as CCME (2000). The following equation is used:

$$SQG_{SI} = \frac{(TDI - EDI) \times SAF \times BW \times 10^3}{SIR \times AF_G \times ET} + [BSC]$$

where:

SQG_{SI}	=	human health soil quality guideline for soil ingestion (mg/kg);
TDI	=	tolerable daily intake (mg/kg-day; chemical-specific parameter);
EDI	=	estimated daily intake (mg/kg-day; chemical-specific parameter);
SAF	=	soil allocation factor (dimensionless; chemical-specific parameter);
BW	=	body weight (kg; see Table 2.4);
10^3	=	conversion factor from kg to g;
SIR	=	soil ingestion rate (g/day; see Table 2.4);
AF_G	=	absorption factor for gut (dimensionless; chemical-specific parameter);
ET	=	exposure term (dimensionless; see Table 2.4); and,
BSC	=	background soil concentration (mg/kg; chemical-specific parameter).

3.3 Soil Dermal Contact

The soil quality guideline for soil dermal contact (SQG_{DC}) was calculated in the same way as CCME (2000). The total loading of soil on the body was calculated as the product of exposed skin surface area and dermal loading, and was calculated separately for hands and other skin surfaces. The amount of chemical that gains access to the body following each dermal exposure event was calculated by multiplying the loading of chemical on the skin (*i.e.*, soil loading multiplied by soil concentration) by a dermal absorption factor. The following equation is used:

$$SQG_{DC} = \frac{(TDI - EDI) \times SAF \times BW \times 10^6}{AF_D \times \{ (SA_{HANDS} \times DL_{HANDS}) + (SA_{OTHER} \times DL_{OTHER}) \} \times EF \times ET} + [BSC]$$

where:

SQG_{DC}	=	human health soil quality guideline for soil dermal contact (mg/kg);
TDI	=	tolerable daily intake (mg/kg-day; chemical-specific parameter);
EDI	=	estimated daily intake (mg/kg-day; chemical-specific parameter);
SAF	=	soil allocation factor (dimensionless; chemical-specific parameter);
BW	=	body weight (kg; see Table 2.4);
10^6	=	conversion factor from kg to mg;
AFD	=	absorption factor for dermal (dimensionless; chemical-specific parameter);
SA_{hands}	=	hand surface area (cm ² ; see Table 2.4);
DL_{hands}	=	dermal soil loading for hands (mg/cm ² -event; see Table 2.4);
SA_{other}	=	surface area for other exposed skin (cm ² ; see Table 2.4);
DL_{other}	=	dermal soil loading for other exposed skin (mg/cm ² -event; see Table 2.4);

EF	=	exposure frequency (events/day; see Table 2.4)
ET	=	exposure term (dimensionless; see Table 2.4); and,
BSC	=	background soil concentration (mg/kg; chemical-specific parameter).

3.4 Indoor Vapour Inhalation

The approach taken to calculate the guideline for this pathway is identical to that used in CCME (2000). Essentially, three processes are considered:

1. three-phase partitioning to predict the concentration of a contaminant in soil vapour from the measured concentration of that contaminant in soil;
2. a dilution factor to predict indoor air concentrations from soil vapour concentrations; and,
3. a standard exposure equation to predict exposure dose from indoor air concentration.

These three processes are combined in the following equation for the indoor vapour inhalation guideline:

$$SQG_{II} = \frac{(RfC - C_a) \times [\theta_w + (K_{oc} \times f_{oc} \times \rho_b) + ((H/RT) \times \theta_a)] \times SAF \times DF_i \times 10^3}{(H/RT) \times \rho_b \times ET \times 10^6} + BSC$$

where:

SQG_{II}	=	soil quality guideline for indoor infiltration (mg/kg);
RfC	=	reference air concentration (mg/m ³ ; chemical specific parameter);
C_a	=	background indoor air concentration (mg/m ³ ; chemical specific parameter);
θ_w	=	moisture-filled porosity (dimensionless; see Table 2.1);
K_{oc}	=	organic carbon partition coefficient (mL/g; chemical specific parameter);
f_{oc}	=	fraction organic carbon (g/g; see Table 2.1);
ρ_b	=	dry bulk density (g/cm ³ ; see Table 2.1);
H	=	Henry's Law Constant (atm-m ³ /mol; chemical specific parameter);
R	=	gas constant (8.2 x 10 ⁻⁵ atm-m ³ /mol-°K);
T	=	soil temperature (°K; Table 2.1);
θ_a	=	vapour-filled porosity (dimensionless; see Table 2.1);
SAF	=	soil allocation factor (dimensionless; chemical-specific parameter);
DF_i	=	dilution factor from soil gas to indoor air (dimensionless; see derivation below);
10^3	=	conversion factor from kg to g;
ET	=	exposure term (dimensionless; see Table 2.4);
10^6	=	conversion factor from m ³ to cm ³ ; and,
BSC	=	background soil concentration (mg/kg; chemical specific parameter).

Definition of Attenuation Coefficient (α)

The attenuation coefficient (α) is defined as the inverse of the dilution factor. Accordingly, the dilution factor may be calculated as:

$$DF_I = \frac{1}{\alpha}$$

where:

- DF_I = dilution factor from soil gas concentration to indoor air concentration (dimensionless); and,
 α = attenuation coefficient (dimensionless; derived below)
= (contaminant vapour concentration in the building)/(vapour concentration at the contaminant source).

3.4.1 Calculation of α - General Considerations

Calculation of the attenuation coefficient (α) is a critical step in the derivation of this guideline. The approach used is based on work by Johnson and Ettinger (1991), who consider two vapour transport processes:

1. far from the building foundation, diffusive transport of volatile contaminants in the soil is assumed to be the dominant vapour transport mechanism; and,
2. close to the building foundation, it is assumed that advective transport towards and through floor cracks, driven by the pressure differential between ambient conditions and the inside of a building, will be the dominant mechanism.

They derive an equation for α in the general case where both these processes are significant. However, following the approach taken in CCME (2000), the limiting case of this equation considering advection only is used for coarse soils, and the limiting case considering diffusion only is used for fine soils. For modified generic or site-specific guidelines, the full equation, considering both advection and diffusion is used.

3.4.2 Calculation of α for Coarse Soils

As noted above, the attenuation coefficient for coarse soils was calculated using the limiting case of the Johnson and Ettinger (1991) equation for cases where only advective transport is significant:

$$\alpha = \frac{\left(\frac{D_T^{eff} A_B}{Q_B L_T} \right)}{\left(\frac{D_T^{eff} A_B}{Q_{soil} L_T} \right) + 1}$$

where:

α	=	attenuation coefficient (dimensionless);
D_T^{eff}	=	effective porous media diffusion coefficient (cm ² /s; derived below);
A_B	=	building area (cm ² ; see Table 3.1);
Q_B	=	building ventilation rate (cm ³ /s; derived below);
L_T	=	distance from contaminant source to foundation (cm; see Table 3.1); and,
Q_{soil}	=	volumetric flow rate of soil gas into the building (cm ³ /s; derived below).

Calculation of D_T^{eff} :

$$D_T^{eff} \approx D_a \times \left(\frac{\theta_a^{10/3}}{\theta_t^2} \right)$$

where:

D_T^{eff}	=	overall effective porous media diffusion coefficient based on vapour-phase concentrations for the region between the source and foundation (cm ² /s);
D_a	=	diffusion coefficient in air (cm ² /s; chemical specific parameter);
θ_a	=	vapour-filled porosity (dimensionless; see Table 2.1); and,
θ_t	=	total soil porosity (dimensionless; see Table 2.1).

Calculation of Q_B :

$$Q_B = \frac{L_B \times W_B \times H_B \times ACH}{3,600}$$

where:

Q_B	=	building ventilation rate (cm ³ /s);
L_B	=	building length (cm; see Table 3.1);
W_B	=	building width (cm; see Table 3.1);
H_B	=	building height, including basement (cm; see Table 3.1);
ACH	=	air exchanges per hour (h ⁻¹ ; see Table 3.1); and,
3,600	=	conversion factor from hours to seconds.

Calculation of Q_{soil} :

$$Q_{soil} = \frac{2 \times \pi \times \Delta P \times k_v \times X_{crack}}{\mu \times \ln \left[\frac{2 \times (Z_{crack})}{r_{crack}} \right]}$$

where:

Q_{soil}	=	volumetric flow rate of soil gas into the building (cm^3/s);
ΔP	=	pressure differential ($\text{g}/\text{cm}\cdot\text{s}^2$; see Table 3.1);
k_v	=	soil permeability to vapour flow (cm^2 ; see Table 2.1);
X_{crack}	=	length of idealized cylinder (cm ; see Table 3.1);
μ	=	vapour viscosity ($\text{g}/\text{cm}\cdot\text{s}$; chemical specific parameter);
Z_{crack}	=	distance below grade to idealized cylinder (cm ; see Table 3.1); and,
r_{crack}	=	radius of idealized cylinder (cm ; see Table 3.1).

3.4.3 Calculation of α for Fine Soils

As noted above, the attenuation coefficient for fine soils was calculated using the limiting case of the Johnson and Ettinger (1991) equation for cases where only diffusive transport is significant:

$$\alpha = \frac{\left(\frac{D_T^{\text{eff}} A_B}{Q_B L_T} \right)}{1 + \left(\frac{D_T^{\text{eff}} A_B}{Q_B L_T} \right) + \left(\frac{D_T^{\text{eff}} A_B L_{\text{crack}}}{D_{\text{crack}} A_{\text{crack}} L_T} \right)}$$

where:

α	=	attenuation coefficient (dimensionless);
D_T^{eff}	=	effective porous media diffusion coefficient (cm^2/s ; see *);
A_B	=	building area (cm^2 ; Table 3.1);
Q_B	=	building ventilation rate (cm^3/s ; see *);
L_T	=	distance from contaminant source to foundation (cm ; Table 3.1);
L_{crack}	=	thickness of the foundation (cm ; Table 3.1);
D_{crack}	=	effective vapour-pressure diffusion coefficient through the crack (cm^2/s ; Table 3.1); and,
A_{crack}	=	area of cracks through which contaminant vapours enter building (cm^2 ; Table 3.1).

* The parameters D_T^{eff} and Q_B were calculated using the same equations as for coarse soil (see Section 3.4.2 above).

3.4.4 Calculation of α Using Site-Specific Soil Properties

Modified generic guidelines (Tier 2) or site-specific guidelines (Tier 3) may be calculated for this pathway using the above approach by substituting site-specific values for one or more of the parameters in the equations. Guidance is provided in Volume 3 (User Guidance) as to which parameters may be

changed at Tier 2, and what information is required to justify using site-specific parameters. For Tier 2 and Tier 3 calculations, the full Johnson and Ettinger (1991) equation for α should be used:

$$\alpha = \frac{\left(\frac{D_T^{\text{eff}} A_B}{Q_B L_T} \right) \exp\left(\frac{Q_{\text{soil}} L_{\text{crack}}}{D_{\text{crack}} A_{\text{crack}}} \right)}{\exp\left(\frac{Q_{\text{soil}} L_{\text{crack}}}{D_{\text{crack}} A_{\text{crack}}} \right) + \left(\frac{D_T^{\text{eff}} A_B}{Q_B L_T} \right) + \left(\frac{D_T^{\text{eff}} A_B}{Q_{\text{soil}} L_T} \right) \left[\exp\left(\frac{Q_{\text{soil}} L_{\text{crack}}}{D_{\text{crack}} A_{\text{crack}}} \right) - 1 \right]}$$

where:

α	=	attenuation coefficient (dimensionless);
D_T^{eff}	=	effective porous media diffusion coefficient (cm ² /s; see *);
A_B	=	building area (cm ² ; Table 3.1);
Q_B	=	building ventilation rate (cm ³ /s; see *);
L_T	=	distance from contaminant source to foundation (cm; Table 3.1);
Q_{soil}	=	volumetric flow rate of soil gas into the building (cm ³ /s; see *);
L_{crack}	=	thickness of the foundation (cm; Table 3.1);
D_{crack}	=	effective vapour diffusion coefficient through the crack (cm ² /s; Table 3.1); and,
A_{crack}	=	area of cracks through which contaminant vapours enter the building (cm ² ; Table 3.1).

The parameters D_T^{eff} , Q_B , and Q_{soil} were calculated using the same equations as for coarse soil (see Section 3.4.2 above).

3.5 Protection of Potable Groundwater

The guideline for protection of potable groundwater (SQG_{GW}) was calculated in the same way as CCME (2000), though different parameters are used in calculating the dilution factors for coarse and fine soil. The basis of the calculation is as follows: the partitioning coefficient ($K_{oc} f_{oc}$) and soil moisture content were used to link the measured soil concentration with the pore water concentration. Next a dilution factor was calculated, linking concentrations in soil pore water adjacent to the source to concentrations in groundwater immediately below. This calculation is based on recharge rate, site length, and aquifer parameters, and is used to link pore water concentrations to “reasonable worst case” groundwater concentrations. Thus a conservative relationship between measured soil concentration and groundwater concentration is established. The following equation is used:

$$SQG_{GW} = \frac{(TDI - EDI) \times ((K_{oc} \times f_{oc}) + (\theta_m / \rho_w)) \times BW \times DF_w}{IR_w} + BSC$$

where:

SQG_{GW}	=	soil quality guideline for protection of potable groundwater (mg/kg);
TDI	=	tolerable daily intake (mg/kg-day; chemical-specific parameter);
EDI	=	estimated daily intake (mg/kg-day; chemical-specific parameter);
K_{oc}	=	organic carbon partition coefficient (mL/g; chemical specific parameter);
f_{oc}	=	fraction organic carbon (g/g; see Table 2.1);
θ_m	=	ratio of mass of water in soil/dry mass of soil (g/g; see Table 2.1);
ρ_w	=	density of water (g/cm ³ ; see Table 3.2);
BW	=	body weight (kg; see Table 2.4);
DF_w	=	groundwater/pore water dilution factor (dimensionless; calculated below);
IR_w	=	ingestion rate of water (L/day; see Table 2.4); and,
BSC	=	background soil concentration (mg/kg; chemical-specific parameter).

Not that a soil allocation factor was not included in the equation for this pathway consistent with CCME (2000).

The dilution factor was calculated as follows:

$$DF_w = \frac{B \times K \times i}{I \times L} + 1$$

where:

DF_w	=	groundwater/pore water dilution factor (dimensionless);
B	=	effective mixing depth in aquifer (m; see Table 3.2);
K	=	saturated hydraulic conductivity of aquifer (m/y; see Table 2.1);
i	=	hydraulic gradient (dimensionless; see Table 3.2);
I	=	recharge rate (m/y; see Table 2.1); and,
L	=	site length (m; see Table 3.2).

The calculation of the protection of potable groundwater guideline in this document differs from the approach used in CCME (2000) only in the value of one parameter. Groundwater recharge (Table 3.2) is set to Alberta-specific values of 0.060 m/year and 0.012 m/year for coarse and fine soil, respectively.

These values are based on extensive research by Atomic Energy of Canada Limited (AECL, 1990, 1991, 1992, and 1995) and hydrogeological literature for the prairies (e.g., Trudell, 1994; Keller *et al.*, 1986; Woo and Rowsell, 1993). This work is consistent with groundwater recharge being less than 10% of precipitation in Coarse soils and less than 2% of precipitation in Fine soils. Taking these values together with precipitation data for the wettest of the Alberta locations for which climate normals are available (Edson: precipitation = 568 mm/year, based on 1961 to 1990 Canadian Climate Normals, Environment Canada, 2001) and rounding up, gives recharge values of 60 mm/year, and 12 mm/year for Coarse and Fine soils, respectively.

Note that, consistent with CCME (2000), the value for the saturated hydraulic conductivity of Fine soils (Table 2.1) was 32 m/year, reflecting the fact that aquifers with saturated hydraulic conductivities less than this are unlikely to provide sufficient yield to supply the drinking water for a residence.

Note also that the mixing depth, B, is assumed to be 2 m (CCME, 2000). This value is based on the typical minimum screened length for a domestic water well, due to the mixing of water that will occur within the screened interval. No such mixing typically occurs when groundwater is discharged at a spring or creek, and accordingly the mixing depth for the ecological protection of groundwater pathways is smaller (Section 4.5.6).

3.6 Example Calculation for Carcinogenic Chemicals

Guidelines for carcinogenic chemicals (benzene and B(a)P) are calculated in a similar way to those for non-carcinogenic chemicals with the following differences:

- the risk-specific concentration (RsC), evaluated at an excess cancer risk of 1 in 100,000, is used in place of the reference concentration (RfC);
- the risk-specific dose (RsD), evaluated at an incremental cancer risk of 1 in 100,000, is used in place of the tolerable daily intake (TDI);
- background exposure is not considered, as guidelines are based on excess cancer risk above background;
- exposure to carcinogens is evaluated for lifetime exposure (CCME, 1996); and,
- adults, rather than toddlers, are used as the receptor of concern in all land uses.

The soil quality guidelines calculated for benzene for the soil ingestion pathway (SQG_{SI}) were calculated using the following equation:

$$SQG_{SI} = \frac{RsD \times SAF \times BW \times 10^3}{SIR \times AF_G \times ET}$$

Where:	SQG_{SI}	=	human health soil quality guideline for soil ingestion (mg/kg);
	RsD	=	risk-specific dose evaluated at an excess cancer risk of 1 in 100,000 (mg/kg-bw/day; chemical-specific parameter);
	SAF	=	soil allocation factor (dimensionless; chemical-specific parameter);
	BW	=	adult body weight (kg; Table 2.4);
	10^3	=	conversion factor from kg to g;
	SIR	=	soil ingestion rate for the adult (g/day; Table 2.4);
	AF_G	=	absorption factor for gut (dimensionless; chemical-specific parameter); and,
	ET	=	exposure term for residential use (dimensionless; Table 2.4).

4. ECOLOGICAL HEALTH SOIL GUIDELINES

4.1 General Considerations

The procedures for calculating guidelines for each of the pathways listed in Section 2.7.3 are detailed in the following sections. Some considerations that apply to all pathways are discussed below. Much of this section is based on protocols published in CCME (1996), and refined in CCME (2000). Where appropriate, reference is made to specific sections in these documents.

Regulatory exposure limits are generally not available for ecological endpoints, and accordingly exposure limits may have to be developed from available and applicable toxicological data. Exposure limits are developed in the guideline development work (Volume 2), using methods previously developed by the CCME (1996 and 2000), and adapted where appropriate. The main departures from the above-noted protocols involve increased emphasis on professional judgement in assessing the toxicological data. In particular, the emphasis in this document is on generating guidelines for pathways whenever it is scientifically justified to do so from the available toxicological dataset. The rationale for this is that it is normally easier to make sound management decisions for contaminated sites with some guideline for a particular pathway than with no guideline for that pathway.

In the sections which follow, reference is made to procedures published in CCME (1996, 2000). The relevant parts of these procedures are summarized in the following sections, but the reader is referred to the original documents for further detail and background information.

4.2 Ecological Exposure Limits

Three main groups of ecological receptors are considered, each with its own exposure limit:

1. The exposure limit for plants and soil invertebrates is expressed as a concentration in units of mg/kg and is adopted directly as the soil contact guideline. General principles used in calculating this guideline are discussed in Section 4.3. The derivation of the exposure limit and guideline for each chemical is provided in Volume 2.
2. The exposure limit for freshwater aquatic life is expressed as a concentration in units of mg/L and is adopted directly as the protection of groundwater for aquatic life guideline. The values for this exposure limit are adapted directly from CCME (1999) values where available, or are derived using CCME (1999) protocols. Details for each chemical are provided in Volume 2.

3. The exposure limit for mammalian (non-human) receptors is expressed as a dose in units of mg/kg-bw/day and is referred to as the daily threshold effect dose (DTED). The DTED is used to calculate the livestock/wildlife soil ingestion and the livestock/wildlife watering guidelines. The DTED for each chemical is calculated in Volume 2, and is based on either livestock or laboratory animal toxicological data depending on availability. An uncertainty factor is applied to the toxicological data to derive the DTED. The value of the uncertainty factor depends on the quality of the toxicological data and the scope of the experiment.

4.3 Plant/Invertebrate Soil Contact

The guideline for this pathway is derived from data collected specifically for this project, and is discussed in Volume 2.

4.4 Soil Ingestion (Livestock/Wildlife)

A protocol is provided to calculate a guideline for livestock/wildlife soil and food ingestion in Section B7.6 of CCME (1996). However insufficient toxicological or bioconcentration data exist to calculate this guideline for any of the chemicals of concern. Accordingly two modifications to this protocol are used in the present work:

1. Only soil ingestion is considered. Petroleum hydrocarbons do not tend to bioconcentrate into the food web (e.g., Suter 1997). Accordingly it is anticipated that exposure by livestock and wildlife to chemicals of concern via food ingestion will be a minor pathway in comparison to soil ingestion.
2. A livestock/wildlife Daily Threshold Effect Dose (DTED) is developed for each chemical of concern by extrapolation from studies on laboratory animals using appropriate uncertainty factors. Uncertainty factors are selected using some of the same rationale used for developing human health exposure limits, and is discussed for each chemical in Volume 2.

A guideline for this pathway was calculated using a dairy cow for agricultural land use, and a mule deer for natural areas. Receptor parameters are summarized in Table 2.5. The following equation was used:

$$SQG_{ESI} = \frac{0.75 \times DTED \times BW \times 1,000}{SIR \times BF}$$

where:

SQG_{ESI}	=	ecological quality guideline for soil ingestion (mg/kg);
0.75	=	factor to prevent animals from being exposed to more than 75% of the DTED (dimensionless; CCME, 1996);
DTED	=	daily threshold effect dose (mg/kg-day; chemical-specific parameter);

BW	=	body weight (kg; see Table 2.5);
1,000	=	conversion factor from kg to g;
SIR	=	soil ingestion rate (g/day; see Table 2.5); and,
BF	=	bioavailability factor (dimensionless; assumed to be 1.0).

4.5 Protection of Groundwater – Ecological Receptors

4.5.1 General Considerations

This pathway considers the allowable concentrations in soil that will not cause unacceptable concentrations in natural surface water bodies or dugouts for two groups of receptors: 1) freshwater aquatic life, and 2) livestock or mammalian wildlife species. The methodology used for protection of surface water quality follows CCME (2000), and differs from that used to calculate the protection of potable groundwater pathway in this document, and the methodology used for the protection of groundwater for aquatic life in CCME (1996) by introducing a minimum 10 m lateral offset between source and exposure point (*i.e.*, surface water body). The model and parameters used to relate the concentration of a contaminant in soil to that in a surface water body are discussed in the following sections. Parameters used in the model are summarized in Table 4.1. Dugouts are handled somewhat differently as described in Section 6.2.2.

The protection of groundwater for freshwater aquatic life applies to all land uses, and the guideline for each chemical of concern was derived from the water quality guideline for freshwater aquatic life for that chemical. Where available, CCME (1999) water quality guidelines are used. Otherwise, water quality guidelines are developed in Volume 2, using guidance from Section 6 of this document.

The protection of groundwater for livestock/ wildlife watering applies only to agricultural land use (using dairy cows as receptors) and to natural areas (using mule deer as receptors). Tolerable daily intakes of chemicals of concern, and tolerable concentrations for drinking water for these receptors are developed in Volume 2.

4.5.2 Model Overview

The protection of groundwater model is the same as that used by CCME (2000), which, in turn is based on BCMELP (1996). The model considers four processes:

1. partitioning from soil to leachate;
2. transport of leachate from base of contamination to water table;
3. mixing of leachate and groundwater; and,
4. groundwater transport downgradient to a discharge point.

For each of these four processes, a dilution factor was calculated (DF1 through DF4, respectively). DF1 has units of (mg/kg)/(mg/L) or L/kg. The other three dilution factors are dimensionless (units of (mg/L)/(mg/L)). The overall dilution factor is used to calculate the soil concentration that is protective of a particular surface water guideline (aquatic life, livestock, or wildlife) using the following equations:

$$SQG_G = C_w DF$$

$$DF = DF1 \times DF2 \times DF3 \times DF4$$

where:

SQG_G	=	soil quality guideline protective of groundwater for aquatic life, livestock, or wildlife watering (mg/kg);
C_w	=	water quality guideline for aquatic life, livestock, or wildlife watering (mg/L; chemical-specific parameter);
DF	=	overall dilution factor (L/kg);
$DF1$	=	dilution factor 1, (L/kg; calculated in following sections);
$DF2$	=	dilution factor 2, (dimensionless; calculated in following sections);
$DF3$	=	dilution factor 3, (dimensionless; calculated in following sections); and,
$DF4$	=	dilution factor 4, (dimensionless; calculated in following sections).

The assumptions made by the model and the equations that describe the four processes are discussed in the following four sections.

4.5.3 Model Assumptions

Assumptions implicit in the model include the following:

- the soil is physically and chemically homogeneous;
- the moisture content is uniform throughout the unsaturated zone;
- the infiltration rate is uniform throughout the unsaturated zone;
- decay of the contaminant source is not considered (*i.e.*, infinite source mass);
- flow in the unsaturated zone is assumed to be one dimensional and downward only (vertical recharge) with dispersion, sorption-desorption, and biological degradation;
- the contaminant is not present as a free phase product;
- the maximum concentration in the leachate is equivalent to the solubility limit of the chemical in water under the defined site conditions;
- the groundwater aquifer is unconfined;
- groundwater flow is uniform and steady;
- co-solubility and oxidation/reduction effects are not considered;
- attenuation of the contaminant in the saturated zone is assumed to be one dimensional with respect to sorption-desorption, dispersion, and biological degradation;

- dispersion is assumed to occur in the longitudinal and transverse directions only and diffusion is not considered;
- mixing of the leachate with the groundwater is assumed to occur through mixing of leachate and groundwater mass fluxes; and,
- dilution of the plume by groundwater recharge down-gradient of the source is not included.

4.5.4 Dilution Factor 1

Dilution factor 1 (DF1) is the ratio of the concentration of a contaminant in soil to the concentration in leachate that is in contact with the soil. This “dilution factor” represents the three phase partitioning between contaminant sorbed to soil, contaminant dissolved in pore water (*i.e.*, as leachate) and contaminant present as soil vapour. DF1 was calculated using the following equation:

$$DF1 = K_{oc}f_{oc} + \frac{(\theta_w + H'\theta_a)}{\rho_b}$$

where:

DF1	=	dilution factor 1 (L/kg);
K_{oc}	=	organic carbon partition coefficient (mL/g; chemical specific parameter);
f_{oc}	=	fraction organic carbon (g/g; see Table 2.1);
θ_w	=	moisture-filled porosity (dimensionless; see Table 2.1);
H'	=	dimensionless Henry’s Law constant (chemical specific parameter);
θ_a	=	vapour-filled porosity (dimensionless; see Table 2.1); and,
ρ_b	=	dry soil bulk density (g/cm ³ ; see Table 2.1).

4.5.5 Dilution Factor 2

Dilution factor 2 (DF2) is the ratio of the concentration of a contaminant in leachate that is in contact with the soil, to the concentration in pore water just above the groundwater table. This dilution factor reflects a decrease in concentration as dissolved contaminant moves downwards from the base of contamination through the unsaturated zone to the water table. The decrease in concentration is due to two processes: i) dispersion in the unsaturated zone, and ii) biodegradation in the unsaturated zone. For Tier 1 calculations, the contaminant is assumed to extend to the water table, and so there is no decrease in concentration due to these processes and DF2 = 1.0. However, the equations for calculating DF2 are included here because they may be used in Tier 2 or 3 calculations.

$$DF2 = \exp \left\{ \frac{b}{2D_u} \left[\left(1 + \frac{4D_u L_{us}}{v_u} \right)^{1/2} - 1 \right] \right\}$$

$$D_u = \frac{b}{10}$$

$$L_{us} = \left(\frac{0.691}{t_{1/2us}} \right) \left(1 - \frac{D_{1/2us}}{365} \right) \exp(-0.07d)$$

$$v_u = \frac{IR_u}{\theta_w}$$

$$R_u = 1 + \frac{\rho_b K_{oc} f_{oc}}{\theta_w}$$

where:

DF2	=	dilution factor 2 (dimensionless);
b	=	distance from base of contamination to water table (0 m; see Table 4.1);
D _u	=	dispersion in unsaturated zone (m; calculated above);
L _{us}	=	decay constant for chemical (year ⁻¹ ; calculated above);
v _u	=	mean linear leachate velocity (m/year; calculated above);
t _{1/2us}	=	chemical half life in unsaturated zone (year; chemical specific parameter);
D _{1/2us}	=	mean number of frost free days/year (days; see Table 4.1);
d	=	depth to water table (m; see Table 4.1);
I	=	infiltration rate (m/year; see Table 3.2);
R _u	=	retardation in unsaturated zone (dimensionless; calculated above);
θ _w	=	moisture-filled porosity (dimensionless; see Table 2.1);
ρ _b	=	soil dry bulk density (kg/L; see Table 2.1);
K _{oc}	=	organic carbon partition coefficient (mL/g; chemical specific parameter);
	=	and,
f _{oc}	=	fraction organic carbon (g/g; see Table 2.1).

4.5.6 Dilution Factor 3

Dilution factor 3 (DF3) is the ratio of the concentration of a chemical in pore water just above the groundwater table, to the concentration in groundwater beneath the source. This dilution factor reflects a decrease in concentration as leachate mixes with uncontaminated groundwater. DF3 is a simple function of groundwater velocity, infiltration rate, source length, and mixing zone thickness. The mixing

zone thickness was calculated as being due to two processes: i) mixing due to dispersion, and ii) mixing due to infiltration rate. The equations used are as follows:

$$DF3 = 1 + \frac{Z_d V}{IX}$$

$$Z_d = r + s$$

$$r = 0.01X$$

$$s = d_a \left\{ 1 - \exp\left(\frac{-2.178XI}{Vd_a}\right) \right\}$$

$$V = Ki$$

where:

DF3	=	dilution factor 3 (dimensionless);
Z_d	=	average thickness of mixing zone (m; calculated above);
V	=	Darcy velocity in groundwater (m/year; calculated above);
I	=	infiltration rate (m/year; see Table 3.2);
X	=	length of contaminated soil (m; see Table 4.1);
r	=	mixing depth due to dispersion (m; calculated above);
s	=	mixing depth due to infiltration rate (m; calculated above);
d_a	=	unconfined aquifer thickness (m; see Table 4.1);
K	=	aquifer hydraulic conductivity (m/year; see Table 2.1); and,
i	=	lateral hydraulic gradient in aquifer (dimensionless; see table 3.2).

4.5.7 Dilution Factor 4

Dilution factor 4 (DF4) accounts for the processes of dispersion and biodegradation as groundwater travels downgradient from beneath the source of contamination, and is the ratio of the concentration of a chemical in groundwater beneath the source, to the concentration in groundwater at a distance (10 m for Tier 1) downgradient of the source. The equation used to calculate this dilution factor is based on an analytical groundwater transport model (Domenico, 1987) and considers the following processes:

- advection of dissolved contaminant based on the groundwater advective flow velocity and direction;
- retardation of the advective velocity by organic matter in the aquifer;
- dispersion of the contaminant in two directions – longitudinal (*i.e.*, parallel with the groundwater flow direction, and transverse (*i.e.*, laterally in the horizontal plane); and,
- first order decay of contaminant mass (used to simulate biodegradation through the use of a contaminant half life).

Dilution factor 4 was calculated using the following equations:

$$DF4 = \frac{4}{\exp(A) \operatorname{erfc}(B) [\operatorname{erf}(C) - \operatorname{erf}(D)]}$$

$$A = \frac{x}{2D_x} \left\{ 1 - \left(1 + \frac{4L_s D_x}{v} \right)^{1/2} \right\}$$

$$B = \frac{x - vt \left(1 + \frac{4L_s D_x}{v} \right)^{1/2}}{2(D_x vt)^{1/2}}$$

$$C = \frac{y + Y/2}{2(D_y x)^{1/2}}$$

$$D = \frac{y - Y/2}{2(D_y x)^{1/2}}$$

$$L_s = \frac{0.691}{t_{1/2s}} \exp(-0.07d)$$

$$v = \frac{V}{\theta_i R_i}$$

$$R_i = 1 + \frac{\rho_b K_{oc} f_{oc}}{\theta_i}$$

$$D_x = 0.1x$$

$$D_y = 0.01x$$

where:

- DF4 = dilution factor 4 (dimensionless);
- erf = the error function;
- erfc = the complementary error function;
- A = dimensionless group (defined above);
- B = dimensionless group (defined above);
- C = dimensionless group (defined above);

D	=	dimensionless group (defined above);
x	=	distance to source (m; see Table 4.1);
D_x	=	dispersivity in the direction of groundwater flow (m; calculated above);
L_s	=	decay constant (year^{-1} ; defined above);
v	=	velocity of the contaminant (m/year; defined above);
t	=	time since contaminant release (years; see Table 4.1);
y	=	distance to receptor perpendicular to groundwater flow (m; see Table 4.1);
Y	=	source width (m; see Table 4.1);
D_y	=	dispersivity perpendicular to the direction of groundwater flow (m; calculated above);
$t_{1/2s}$	=	decay half-life of chemical in aquifer (years; chemical specific parameter);
d	=	water table depth (m; see Table 4.1);
V	=	Darcy velocity in groundwater (m/year; defined in Section 4.5.6);
θ_t	=	total soil porosity (dimensionless; see Table 2.1);
R_s	=	retardation factor in saturated zone (dimensionless; defined above);
ρ_b	=	dry soil bulk density (g/cm^3 ; see Table 2.1);
K_{oc}	=	organic carbon partition coefficient (mL/g ; chemical specific parameter); and,
f_{oc}	=	fraction organic carbon (g/g ; see Table 2.1).

5. SOIL TEXTURE AND DEPTH

5.1 General

The guidelines generated in Volume 2 include tables for Coarse and Fine surface soil and subsoil (four tables). The following sections describe how the guidelines differ between Coarse and Fine soil, and between surface soil and subsoil.

5.2 Soil Texture

Differing guidelines for coarse and fine soils are appropriate for certain pathways. The approach used for each pathway is specified below:

5.2.1 Human Health Pathways

- Ingestion – the same guideline applies to coarse and fine soil.
- Soil Dermal Contact – the same guideline applies to coarse and fine soil.

- Indoor Vapour Inhalation – different guidelines were calculated for coarse and fine soil by substituting appropriate soil physical parameters; for details see Section 3.4.
- Protection of Potable Groundwater – different guidelines were calculated for coarse and fine soil by substituting appropriate soil physical parameters; for details see Section 3.5.

5.2.2 Ecological Health Pathways

- Plant/Invertebrate Soil Contact – Separate data were available for Coarse and Fine soil and these data were used in Volume 2 to calculate guidelines for Coarse and Fine soil for this pathway.
- Soil Ingestion – the guideline calculated for this pathway applies equally to coarse and fine soil.
- Protection of Groundwater for Freshwater Aquatic Life and Livestock/Wildlife Watering – appropriate soil parameters are used to calculate separate guidelines for coarse and fine soils; for details see Section 4.5.

5.3 Soil Depth

The approach described in the Sections 3 and 4 of this document can be used to derive guidelines that are suitably protective for surface soils. The guidelines for subsoil (defined as soil at a depth greater than 1.5 m) for certain pathways can be somewhat less stringent, based on a lower likelihood or frequency of contact. The approach to calculating subsoil guidelines taken in this document follows that taken in CCME (2000), and is summarized below.

5.3.1 Human Health Pathways

- Ingestion – not applicable unless ground is disturbed; could apply to occasional exposure for construction workers, but is not expected to be a limiting pathway and is not calculated.
- Soil Dermal Contact – not applicable unless ground is disturbed; could apply to occasional exposure for construction workers, but is not expected to be a limiting pathway and is not calculated.
- Indoor Vapour Inhalation – different guidelines were calculated for sub soil in both the slab-on-grade and basement scenarios by changing the value of parameters Z_{crack} and/or L_T as appropriate; for details see Section 3.4.
- Protection of Potable Groundwater – the same calculation is used for surface soil and sub soil.

5.3.2 Ecological Health Pathways

- Plant/Invertebrate Soil Contact – only very deep-rooted species will be affected by contaminated subsoil, and even for those species, only a fraction of the root mass will be affected. Soil invertebrates spend the majority of their time at depths shallower than 1.5 m, and accordingly

receive only limited exposure to contaminants in subsoil. CCME (2000) generates guidelines for this pathway by multiplying corresponding surface soil guidelines by a factor between 2 and 6. In this document, subsoil guidelines for BTEX are generated by multiplying surface soil guidelines by 2, unless that would put the soil porewater concentration close to solubility for the compound. In such cases the surface soil guideline was adopted directly as the surface soil guideline.

- Soil Ingestion – does not apply as livestock and wildlife will not be directly exposed to subsoil.
- Protection of Groundwater for Freshwater Aquatic Life and Livestock/Wildlife Watering – the same calculation is used for surface soil and sub soil.

6. WATER QUALITY GUIDELINES

Two types of water quality guidelines are defined in this project.

Exposure Point water quality guidelines are applied to the water to which a receptor is actually exposed, and are used in this project as targets for calculating soil guidelines protective of various groundwater uses. Exposure Point water quality guidelines are discussed in Section 6.1 below.

Groundwater quality guidelines provide a reference value to allow a determination of the quality of groundwater, and, for some water uses, take into account the effect of certain transport processes that may occur between the point of groundwater measurement and the receptor. Groundwater quality guidelines are discussed in Section 6.2 below.

6.1 Exposure Point Water Quality Guidelines

The following water uses were considered:

- human drinking water;
- freshwater aquatic life;
- livestock watering; and
- wildlife watering.

Guidelines for F3, F4, and B(a)P were not required, since the low aqueous solubility and high K_{ow} of these hydrocarbons makes it unlikely that exposure to dissolved concentrations of these chemicals in water will be significant.

Where available and appropriate, CCME (1999) water quality guidelines are used. Otherwise, guidelines were calculated for this project. Example calculations are provided in Volume 2 where required.

6.2 Groundwater Quality Guidelines

Groundwater water quality guidelines were derived (Volume 2) from exposure point water quality guidelines to protect the four water uses noted above. The procedure for each water use is discussed below.

6.2.1 Human Drinking Water

The groundwater quality guidelines for human drinking water are adopted directly from the corresponding exposure point water quality guidelines, based on the assumption that a drinking water well could potentially be drilled anywhere within a former upstream oil and gas facility. However, the groundwater quality guidelines for human drinking water need only be applied to aquifers defined as “Domestic Use Aquifers” by AENV (2001).

6.2.2 Livestock Watering

The groundwater quality guidelines for livestock watering are adopted directly from the corresponding exposure point water quality guidelines, based on the assumption that a dugout or water well for livestock watering could potentially be installed anywhere within a former upstream oil and gas facility. The groundwater quality guideline for livestock watering need only be applied where the land use is agricultural.

6.2.3 Freshwater Aquatic Life and Wildlife Watering

Two cases are considered for these two water uses. Separate guidelines are derived for groundwater less than 10 m from the nearest surface water body, and for groundwater more than 10 m from the nearest surface water body.

Groundwater Less Than 10 m From The Nearest Surface Water Body

For groundwater less than 10 m from the nearest surface water body (“the <10 m guidelines”) the exposure point water quality guidelines are adopted directly as groundwater quality guidelines.

Groundwater More Than 10 m From The Nearest Surface Water Body

For groundwater more than 10 m from the nearest surface water body, the guidelines (“the >10 m guidelines”) are less stringent than the corresponding exposure point water quality guidelines. These less stringent guidelines are based on the assumption that groundwater transport processes will result in a decrease in concentration between the point of measurement and a receptor in or drinking from a surface water body. The >10 m guidelines are calculated by dividing the corresponding exposure point water quality guideline by the dilution factor from the saturated transport part of the calculation of the

soil quality guideline for protection of ecological receptors (i.e., DF4 in Section 4.5.7). All the same parameters are used as in the calculation in Section 4.5.7, including the assumed 10 m offset.

The groundwater quality guideline for protection of freshwater aquatic life is applicable to all land uses. The groundwater quality guideline for protection of wildlife watering is only applicable to natural area land use.

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Table 2.1. Generic Soil Properties

<i>Parameter</i>	<i>Symbol</i>	<i>Units</i>	<i>Coarse</i>	<i>Fine</i>
Definition – Median Grain Size is		μm	>75	<75
Soil Temperature ⁽²⁾	T	$^{\circ}\text{K}$	294	294
Total Soil Porosity	θ_T	vol/vol	0.4	0.3
Effective Soil Porosity	θ_E	vol/vol	0.4	0.3
Soil Water Content ($=M_w/M_s$)	θ_M	mass/mass	0.07	0.12
Moisture-Filled Porosity	θ_w	vol/vol	0.119	0.168
Vapour-Filled Porosity	θ_A	vol/vol	0.281	0.132
Soil Bulk Density (Dry Basis)	ρ_b	g/cm^3	1.7	1.4
Soil Permeability to Vapour Flow	k_v	cm^2	10^{-8}	$10^{-9(1)}$
Saturated Hydraulic Conductivity	K	m/y	320	0.32 ⁽²⁾
Recharge Rate ⁽³⁾	R	m/y	0.060	0.012
Fraction of Organic Carbon	f_{oc}	mass/mass	0.005	0.005

NOTES:

ALL PARAMETER VALUES FROM CCME (2000), EXCEPT AS NOTED;

- 1. NOT REQUIRED FOR TIER 1 CALCULATIONS;**
- 2. THIS VALUE IS REPLACED BY 32 M/Y IN THE CALCULATION OF $SQ_{G_{Dw}}$ TO REFLECT THE MINIMUM HYDRAULIC CONDUCTIVITY OF A DOMESTIC USE AQUIFER (DUA); AND,**
- 3. CONSERVATIVE VALUES FOR ALBERTA (SEE TEXT).**

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Table 2.2. Chemicals of Concern

Chemical of Concern	Equivalent Carbon Number Range	Notes
Benzene	na	excluding BTEX compounds excluding carcinogenic PAHs ¹ ; not applicable to vapour or water transport pathways excluding carcinogenic PAHs ¹ ; not applicable to vapour or water transport pathways as benzo(a)pyrene equivalents
Toluene	na	
Ethylbenzene	na	
Xylenes	na	
Fraction F1	6-10	
Fraction F2	>10-16	
Fraction F3	>16-34	
Fraction F4	>34	
Carcinogenic PAHs	na	

NOTES:

Hydrocarbon fractions F1 to F4 defined as per CCME (2000).

1. Carcinogenic PAHs excluded from the definition of these fractions, however, concentrations of carcinogenic PAHs are NOT subtracted from these fractions as explained in the text.

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Table 2.3. Summary of Pathways

Pathway	Natural Areas	Agricultural	Residential	Commercial	Industrial
Human					
Soil Ingestion	-	✓	✓	✓	✓
Soil Dermal Contact	-	✓	✓	✓	✓
Vapour Inhalation (Indoor) ⁽¹⁾	-	✓	✓	✓	✓
Protection of Potable Groundwater ⁽¹⁾	✓	✓	✓	✓	✓
Ecological					
Soil Contact – Plants and Invertebrates	✓	✓	✓	✓	✓
Soil Ingestion – Livestock/Wildlife	✓	✓	-	-	-
Protection of Groundwater for Aquatic Life ⁽¹⁾	✓	✓	✓	✓	✓
Protection of Groundwater for Livestock/Wildlife Ingestion ⁽¹⁾	✓	✓	-	-	-

NOTES:

1. Not calculated for CWS PHC fractions F3, F4 or B(a)P.

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Table 2.4. Human Receptor Parameters

<i>Parameter</i>	<i>Symbol</i>	<i>Units</i>	<i>Toddler</i>	<i>Adult</i>
Age Range		years	0.5-4	20+
Body Weight	<i>BW</i>	kg	16.5	70.7
Indoor Air Inhalation Rate	<i>IR</i>	m ³ /d	9.3	16.2
Water Ingestion Rate	<i>IR_W</i>	L/d	0.6	1.5
Soil Ingestion Rate	<i>SIR</i>	g/d	0.08	0.02
<u>Skin Surface Area</u>				
Hands	<i>SA_{HANDS}</i>	cm ²	430	890
Other ⁽¹⁾	<i>SA_{OTHER}</i>	cm ²	2,580	2,500
<u>Dermal Soil Loading:</u>				
Hands	<i>DL_{HANDS}</i>	mg/cm ² /event	0.1	0.1
Other ⁽¹⁾	<i>DL_{OTHER}</i>	mg/cm ² /event	0.01	0.01
<u>Dermal Exposure</u>				
Frequency	<i>EF</i>	events/day	1	1
<u>Exposure Term (ET) ⁽²⁾</u>				
Natural Areas		(24/24)*(7/7)*(52/52)	1 ⁴	na
Agricultural		(24/24)*(7/7)*(52/52)	1	na
Residential		(24/24)*(7/7)*(52/52)	1	na
Commercial		(10/24)*(5/7)*(48/52)	0.27	na
Industrial		(10/24)*(5/7)*(48/52)	na	0.27
<u>Exposure Duration</u>				
(Carcinogens Only) ⁽³⁾	<i>ED</i>	(expressed as a fraction of a full 70 year lifetime)		
Natural Areas			na	1 ⁴
Agricultural			na	1
Residential			na	1
Commercial			na	1
Industrial			na	1

NOTES:

All values from CCME (2000) unless otherwise specified.

na = not applicable.

1. For adults and teens, "other" = upper and lower arms; for infants, toddlers, and children, "other" = upper and lower arms and upper and lower legs.
2. Exposure term is expressed as a ratio, i.e., 1.0 represents a fully exposed individual; presented only for the critical receptor in each land use.
3. Exposure duration shown as a ratio. As per CCME (1996), the critical receptor for carcinogens is considered to be an adult who is exposed for a full 70-year life.
4. Protection of potable groundwater pathway only.

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Table 2.5. Ecological Receptor Parameters

<i>Parameter</i>	<i>Units</i>	<i>Value</i>	<i>Reference</i>
<i>Dairy Cow</i>			
Body Weight	<i>kg</i>	409	NRC (1996)
Water Ingestion Rate	<i>L/day</i>	64	NRC (1996)
Soil Ingestion Rate	<i>g/day</i>	747	Healy (1968)
<i>Mule Deer</i>			
Body Weight	<i>kg</i>	68	Smith (1993)
Water Ingestion Rate	<i>L/day</i>	4.4	USEPA (1993) ⁽¹⁾
Soil Ingestion Rate	<i>g/day</i>	44	Beyer, <i>et al.</i> (1994) ⁽²⁾

NOTES:

1. USING ALLOMETRIC EQUATIONS FOR WATER INGESTION RATE FROM USEPA (1993).
2. USING ALLOMETRIC EQUATIONS FOR FOOD INGESTION RATE FROM USEPA (1993), AND SOIL CONSUMED AS A PERCENTAGE OF FOOD INTAKE FROM BEYER ET AL. (1994).

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Table 3.1. Parameters for Indoor Air Inhalation Model

Parameter	Symbol	Units	Residential	Residential	Commercial/Industrial
Construction Type			basement	slab on grade	slab on grade
Building Length	L_B	cm	1,225	1,225	2,000
Building Width	W_B	cm	1,225	1,225	1,500
Building Height	H_B	cm	488	488	300
Foundation Thickness	L_{crack}	cm	11.25	11.25	11.25
Distance from Contamination to Slab:	L_T	cm			
Surface Soils			30	30	30
Subsoils			30	139	139
Area of Cracks	A_{crack}	cm ²	995	995	1,850
Length of Idealized Cylinder	X_{crack}	cm	4,900	4,900	7,000
Radius of Idealized Cylinder	r_{crack}	cm	$= A_{crack} / X_{crack}$	$= A_{crack} / X_{crack}$	$= A_{crack} / X_{crack}$
Distance Below Grade to Idealized Cylinder	Z_{crack}	cm	244	11.25	11.25
Air Exchanges Per Hour	ACH	exch/hr	1	1	2
Pressure Differential	ΔP	g/cm-s ²	40	40	20
Diffusivity in Cracks	D_{crack}	cm ² /sec	0.00454	0.00454	0.00454

Notes:

All values from CCME (2000).

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Table 3.2. Parameters for Protection of Potable Groundwater Model

Parameter	Symbol	Units	Value
Effective Mixing Depth	B	m	2
Hydraulic Gradient	i	-	0.05
Site Length	L	m	10
Water Density	ρ_w	g/cm^3	1.0

Notes:
All values from CCME (2000).

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Table 4.1. Parameters for Protection of Groundwater – Ecological Receptors Model

<i>Parameter</i>	<i>Symbol</i>	<i>Units</i>	<i>Value</i>
Contaminant Source Width	X	m	10
Contaminant Source Length	Y	m	30
Distance to Receptor (Parallel to Groundwater Flow)	x	m	10
Distance to Receptor (Perpendicular to Groundwater Flow)	y	m	0
Depth to Groundwater	d	m	3
Distance from Base of Contamination to Groundwater	b	m	0
Depth of Unconfined Aquifer	d _a	m	5
Days With Surface Temp. < 0 deg. C	D _{1/2us}	days	0
Time Since Contaminant Release	t	years	100

Notes:

All values from CCME (2000).

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